

# **Sea Truth Validation of Bio-Optical Models for ‘A’ And ‘B<sub>b</sub>’; Application to Heat Budget Models and the Effects of Biology on Ocean Thermal Structure**

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## **LONG-TERM GOALS**

The long-term goal is to obtain better measurements of the inherent optical properties of seawater (IOPs, absorption ‘a’ and back-scattering ‘b<sub>b</sub>’) to provide better parameterisations of the absorption of light by seawater, to improve heat budget models of surface ocean stratification. The proposed work will extend on-going research at PML on furthering the understanding, accurate interpretation and exploitation of remotely sensed data of ocean colour, from sensors: SeaWiFS, MODIS (NASA), MERIS (ESA). Assimilation of data from these sensors into 1-D and 3-D ocean circulation models is a long-term goal.

## **OBJECTIVES**

The primary objective is to develop bio-optical models, that will have the inherent optical properties (IOPs, absorption ‘a’ and back-scattering ‘b<sub>b</sub>’) as the main variables, so that remotely sensed data of ocean colour can be interpreted and exploited by including the effects of absorption and scattering of solar radiation in heat-budget models of upper-ocean physical structure to improve accuracy. The work with ONR will focus on model validation, acquiring ground-truth data and in situ measurements of the IOPs and AOPs (inter-relationships). The effects of biology (phytoplankton) on vertical thermal structure will be studied.

The development of bio-optical models, with IOPs as the main variables, is on-going and part of the core strategic projects of PML, part funded by NERC. The acquisition of ground truth data of IOPs is new, which ONR/NICOP are requested to provide part-funding.

## **APPROACH**

Year 1 has been focused on the acquisition of new IOP data, which has necessitated the commissioning of new equipment and the development of new optical profiling apparatus, combining existing AOP and new IOP sensors. These developments have been implemented sequentially as new sensors were delivered, so that the on-going (n-year) time series of data acquisition at station L4 in the western

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English Channel was uninterrupted. By this approach we have been able to patch on new data from new sensors to the n-year series of bio-optical data and identify common seasonal features. Existing data sets (n-year = varying length 3-5 year for different variables) exist for: diffuse attenuation coefficients  $k(\lambda)$ , beam-c, remote sensing reflectance  $R()$ , chlorophyll-a, pigments, SPM, coloured dissolved organic matter (CDOM, or  $a_{\text{CDOM}}$ ).

## WORK COMPLETED

Due to a delayed start date (1 Feb 2002) and other factors, variable progress on all fronts has been possible. Prior to the start, PML optics calibration facilities had been upgraded and re-equipped, with a financial package independent of ONR, but to the benefit of the ONR-related research. New facilities, optical benches, calibration standards (lamps, plaques, spheres, detectors, voltmeters) a clean water facility + stainless steel tanks (needed for IOP instrument calibrations) and other optical equipment (Satlantic, SQM II portable calibration facility; Satlantic Micropro freefall optical profiler; Wet Labs ac-9plus and VSF(532 nm); CI beam-c transmissometer (532 nm); Hobo Labs bb-6). Due to the commissioning of these new sensors, the purchase of the ONR equipment was delayed to mid-summer. To the above we have added (ONR funding): Wet Labs ac-9 plus, with more powerful data handling; a VSF3, 3-angle, 3-wavelength volume scattering function and backscattering meter; SBE19plus with 4 a/d inputs, pumps, flow sensors, pressure sensors, patch cables and equipment cables. New stainless steel deployment rigs have been manufactured for deployment of the IOP instrument combinations.

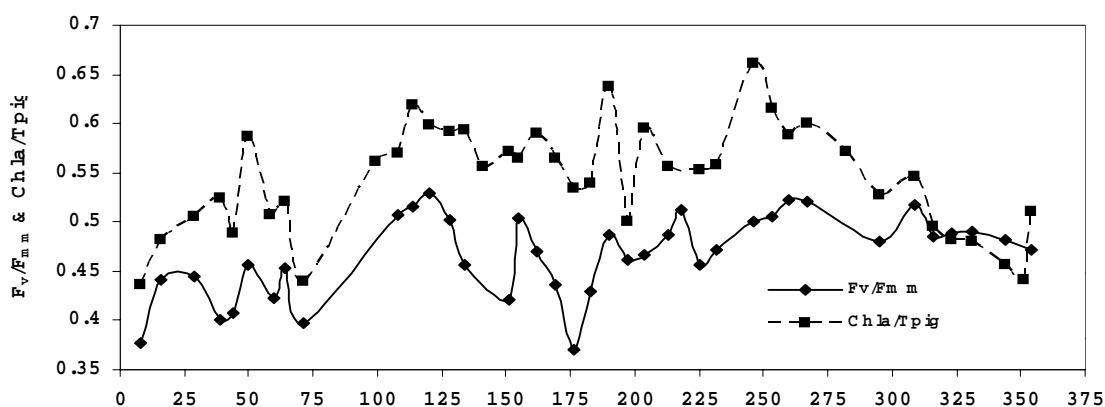
Throughout 2002, the time series of Optical measurements and bio-optical variables at L4 have continued, supplemented since April by new IOP measurements, ac-9 and VSF and later (July) the bb-6. Not all data have been analysed due to incompatibility of manufacturers software in the combinations employed. Supplementary measurements have been taken for pigments, particle absorption, TSM and CDOM. In addition data from all sensors (ac-9, VSF, miniTraka, Ed, Lu, CTD) have been acquired on several research cruises, notably the PML spring cruise on the Celtic Shelf, 1-14 April 2002 (D261, MDB402). The cruise sampled an intense spring bloom of phytoplankton on the shelf close to the shelf break (49 N, 12 W) encountering pre-bloom, bloom (max concentrations of Chla ca  $10 \text{ mg.m}^{-3}$ ) and post bloom (nutrient depleted) conditions. In addition we have made targeted short cruises for specific phytoplankton species (diatoms and coccolithophores). In 2002, regular weekly sampling has been re-started for 2 sites in the Tamar estuary, giving measurements in case 2 waters (low SPM  $10 \text{ mg.l}^{-1}$ ) for comparison with L4 (case 1). Strictly these are beyond the scope of the ONR funded research but the measurement of scattering from suspended inorganic material is valuable. We have been collaborating with a project at U of Plymouth which has developed and tested an Integrating Cavity Absorption meter (ICAM, Kirk) and comparing the data with absorption measurements by ac-9 and PABS (spectrophotometric particle absorption on filter papers). Tables of data acquired for L4 programme and MDB-402 cruise are available.

Finally at the writing of the report, we are about to embark on a SeaWiFS-MODIS-MERIS inter-calibration cruise on the RV AFRICANA in the Benguela ecosystem, S. W. Africa (out of Cape Town) with the full suite of AOP and IOP sensors and ancillary measurements of bio-optically active variables; expected range of chlorophyll from  $0.2$  to  $> 20 \text{ mg.m}^{-3}$ .

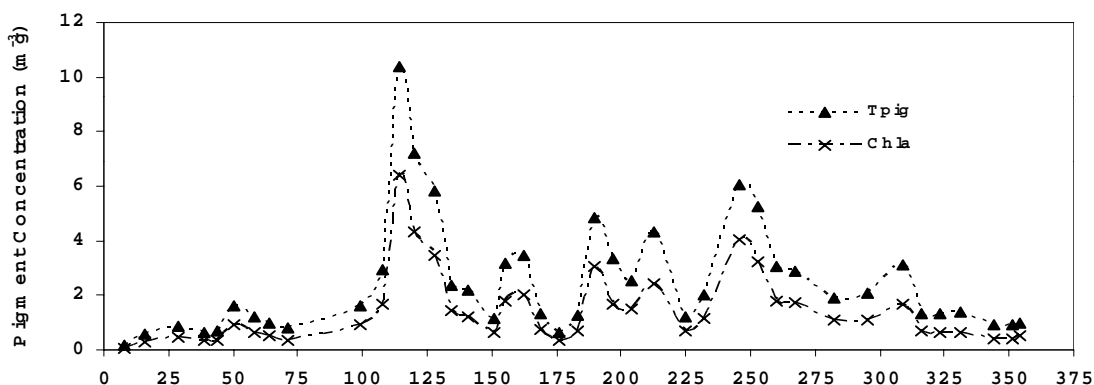
## RESULTS

With the sampling programme for 2002 and the analysis of data for 2002 incomplete (only some pigments have been analysed and other data not processed) we concentrate on results from 2001 which demonstrate the special insights that are provided by seasonal studies.

Station L4 in the western English Channel (WEC) is located at 50 15'N, 04 13'W, 10 km south of Plymouth Breakwater; the nominal depth is 51 m and mean tidal current speed is  $0.25 \text{ cm.s}^{-1}$ . On a few occasions and again monthly in 2002, additional measurements were taken at station E1 (50 02'N, 04 22'W, nominal depth 72 m) about 27 km south from L4. L4 and E1 have been MBA monitoring stations since the 1920s and E1 has been sampled intensively in various PML projects for over a decade. From January to December 2001 measurements by FRRF, CTD and optical profilers (irradiance,  $E_d$  and radiance,  $L_u$ , in 7 wavebands, at SeaWiFS wavelengths) were taken weekly, depending on weather (44 times in 2001; 3 d E1 and 30 times in 2002; 4 d E1 to Sept.). Surface water was filtered for the assay of nutrients and bio-optically active constituents, phytoplankton pigments (by HPLC) particle absorption (PABS), TSM and CDOM.



*Figure 1 Seasonal changes of surface  $F_v/F_{mm}$  and  $Chla/Tpig$  ratio at L4 station for 2001 (the x axis is day of the year).*



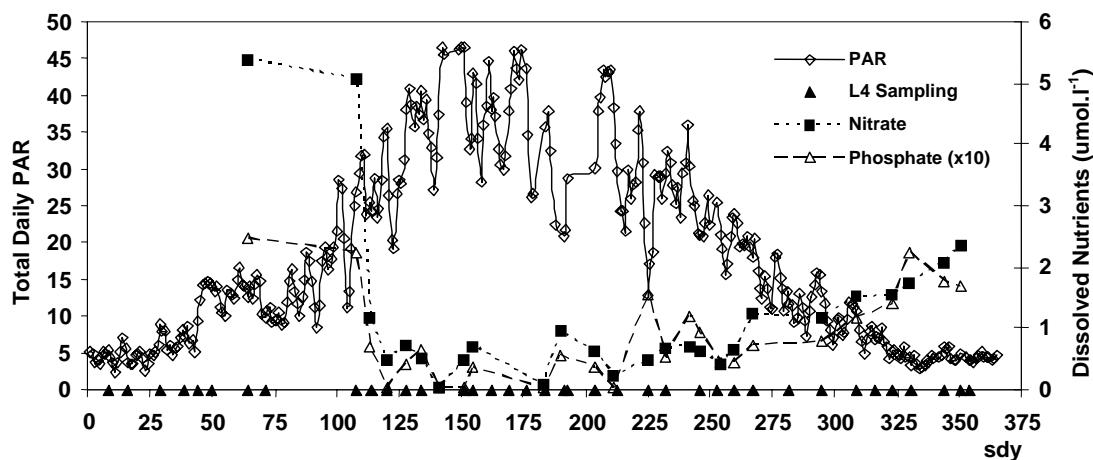
*Figure 2 Seasonal changes of surface  $Chla$  and  $Tpig$  station L4 for 2001 (the x axis is day of the year).*

In the winter (late Sept to March) the water column at L4 is generally totally mixed, except for intermittent salinity stratification, due to a surface layer of fresher water of riverine origin (R. Tamar). The L4 site stratifies from March through to September (optical Case 1) with nutrient depletion of the surface layer in mid-summer. Throughout the WEC there is a succession of phytoplankton blooms from spring to autumn: small diatoms, large diatoms, *Phaeocystis* spp, coccolithophores, *Gymnodinium* spp and *Ceratia* spp. (Holligan and Harbour, 1977).

Figure 1 and figure 2 show the variations of the surface layer values of Chla, Tpig,  $F_v/F_{mm}$  and Chla/Tpig at station L4 for January to December 2001 (sdy = serial day of year). Figure 3 shows the variation of incident solar irradiance measured at a weather station on the University of Plymouth building, 20 km north of the L4 station and surface layer nutrient ( $NO_3$ ,  $PO_4$ ) concentrations.

All the variables (except nutrients) had low values in Jan, rose through the spring, showed episodic fluctuations through the summer and declined in autumn and early winter. The seasonal cycle of pigments and photosynthetic properties had 3 distinct periods:

1. January to mid-May (sdy 8 to 128) mid-winter to spring bloom (LWSB) a ramp-up period;
2. Mid-May to August (sdy 134 to 232) summer stratified with intermittent sub-surface, Chla-maximum in the thermocline (SSTM), a period of episodic events;
3. September-December, autumn bloom (AB, sdy 246 to 295) and early winter (EW, sdy 309 to 354), a ramp-down period.



**Figure 3 Seasonal changes in surface nutrients at station L4 and solar irradiance (PAR, mol quanta.m<sup>-2</sup>.s<sup>-1</sup>) at Plymouth site 2km north of station L4 (the x axis is day of the year).**

In the LWSB period, the surface layer values of Chla, Tpig and  $F_v/F_m$  were all low initially, as photosynthesis was limited by low light just after the winter solstice, even with nutrients surplus. Chla and  $F_v/F_{mm}$  were 0.09 and 0.38 in early Jan (sdy 8) rising to 0.44 and 0.45 (sdy 29), before falling to 0.34 and 0.41 in early Feb (sdy 44). Throughout the low-light late winter period,  $F_v/F_{mm}$  fluctuated weekly between 0.4 and 0.46, correlated with changes of the prevailing weather, incipient stratification and water column instability, noticeably increasing during periods of higher sunlight (fig 3c) and calmer weather and declining in the duller and windier periods. Pigments (Chla and Tpig) and the Chla/Tpig ratio fluctuated in coincidence with  $F_v/F_{mm}$ , though only the relationship Chla/Tpig to

$F_v/F_{mm}$  was correlated significantly. These correlations of phytoplankton pigments and  $F_v/F_{mm}$  with the fluctuations of ambient light were consistent with the environmental conditions of nutrient surplus but light limitation, causing the rates of photosynthesis to be related directly to light intensity (daily total photon budget).

After the equinox, Chla, Tpig, Chla/Tpig and  $F_v/F_{mm}$  all increased: Chla rose from 0.35 to 1.7 mg.m<sup>-3</sup> from mid March to mid April, whilst Chla/Tpig and  $F_v/F_{mm}$  rose from lows of 0.44 and 0.40 respectively to 0.57 and 0.51. The post-equinox surge of solar radiation created a positive heat budget, surface heating, stratification and water column stability, which trapped cells in the surface high light regime, causing the spring bloom. After stable stratification was established in April, the spring bloom peaked with exceptionally high values of Chla and Tpig (6.4 and 10.4 mg.m<sup>-3</sup>) in May (sdy 114) with comparably high values of Chla/Tpig (0.62) and  $F_v/F_{mm}$  (0.52). Surface layer nutrients, declined but remained in surplus.

During the SSTM period, the surface layer nutrients were depleted with low Chla concentration and a sub-surface maximum of phytoplankton biomass in the thermocline. For the L4 study in 2001, pigments were measured only for the surface layer. Fluctuations of Chla and Tpig and  $F_v/F_{mm}$  for the surface layer occurred throughout the early summer (May-June) due to episodic nutrient injections to the surface layer, producing periodic increases of  $F_v/F_{mm}$  which led to surface-layer phytoplankton blooms with Chla concentrations of 2-3 mg.m<sup>-3</sup>. These summer blooms are common occurrences in the western English Channel, though the mechanism of their on-set is not understood fully.

The autumn phytoplankton bloom is another regular occurrence in the WEC usually the dominated by *Ceratia* spp. In 2001 the bloom reached an unusually high concentration of 4.0 mg.m<sup>-3</sup> Chla (6.1 mg.m<sup>-3</sup> Tpig) on sdy 246, with correspondingly high values of 0.66 and 0.5 for Chla/Tpig and  $F_v/F_{mm}$ . Unusually *Gymnodinium* spp were most abundant in 2001. After this peak, there was a downward trend of pigments, Chla/Tpig and  $F_v/F_{mm}$  through the autumn and early winter period, though the negative slopes of Chla/Tpig and  $F_v/F_{mm}$  differed markedly. At this time of year the measurements may have been aliased by sampling in good weather, calm and sunny conditions. Rough weather (with dull illumination) restricted the opportunities for sampling using small boats.

The regression analysis of Chla/Tpig vs  $F_v/F_{mm}$  for the whole year, the LWSB, LWSB + SSTM and ABEW periods, showed significant correlation between these 2 parameter values. For the whole year ( $R^2 = 0.35$ ) the correlation was significant at 0.001 but for seasonal periods the correlations were better: LWSB,  $R^2 = 0.78$ ,  $p < 0.001$ ; LWSB +SS,  $R^2 = 0.72$ ,  $p < 0.001$ . The relationship is also significant in the ABEW, ramp-down period ( $R^2 = 0.58$ ,  $p < 0.001$ ). These results show that in natural ecosystems, phytoplankton adjust their Chla concentration in accordance with the rates of photosynthetic activity ( $PQE_m$  or  $F_v/F_{mm}$ ). The inference is that this is a functional link between Chla and primary production. We conclude that plants maintain their Chla concentration at the level needed to sustain the maximum growth rate in the environment. In other words, Chla concentration is self-regulating, in response to the limitations imposed by other growth substrates, mainly macro or micro nutrient concentrations, light climate and photon availability.

The seasonal variation of the fraction of Chla of total phytoplankton pigments (photosynthetic plus non-photosynthetic) in the WEC in 2001, followed a pattern that fitted the seasonal variation of photosynthetic activity. There was a 'ramp-up' in the late winter and spring, with fluctuations due to variability of light and stratification (windiness and roughness). In summer there were fluctuations due to variability of stratification and nutrient injections from below the thermocline. In the autumn, after

a 'bloom' there was a steady 'ramp-down' to low value in mid-winter. Thus the correlation of Chla/Tpig to PQE is fully expected. It is known that both the synthesis of Chla by plants and its sustenance are energetically demanding compared to other pigment and carbon constituents. Analysis of published data from the Iron enrichment experiments, IronEx II (Behrenfeld et al, 1996; Coale et al 1996) and SOIREE (Boyd et al 2000; Boyd and Abraham, 2001) show significant correlations between Chla/Tpig and PQE.

There are implications for the remote sensing of phytoplankton production from ocean colour data. Many remote sensing algorithms for Chla (e.g. Aiken et al. 1995; O'Reilly et al. 1998) use the ratio of remotely sensed reflectance (Rrs) for 2 bands at 490 and 555 nm. Both of these bands lie outside the Chla absorption band and in reality they are carotenoid or total pigment algorithms. They work because Chla and the accessory pigments, mainly carotenoids co-vary robustly. The inter-province variance of the Chla/carotenoid ratio is probably the main source of error in global Chla algorithms. We have shown here that the seasonal variation of Chla/Tpig (or Chla/Carotenoid) is highly variable, albeit in a biological meaningful pattern. This contradicts the inherent assumption of band ratio algorithms that Chla, accessory pigments and other co-existing bio-optically active constituents are auto-correlated. Models for the determination of primary production from ocean colour data, which use remotely sensed Chla as the main variable, compound these errors. Chla has a distinct blue spectral signature, absorbing from 400-470 nm, while the carotenoids absorb from 400-560 nm (Bidigare et al 1990). Reconstructed phytoplankton absorption spectra show large changes at 443 nm for the range of Chla/Tpig reported here (0.38 to 0.66) and modelled Rrs ratios change by a factor up to 1.5. The inference is that Chla/Tpig can be detected in ocean colour spectra.

## **IMPACT**

We are developing new ac-9 scattering correction procedures using experimental data from ICAM and VSF tank experiments, with various concentrations of particulates.

## **TRANSITIONS**

nil

## **RELATED PROJECTS**

Work with space agencies NASA and ESA on sensor validation as preparatory to exploitation of ocean colour data for IOP measurements (a, bb).

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## **PUBLICATIONS**

nil

## **PATENTS**

nil